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REAL-TIME TROPICAL CYCLONE PREDICTION USING COAMPS-TC

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A new version of the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC$^{\mathrm{TM}}$) has been developed specifically for forecasting tropical cyclone track, structure, and intensity. The COAMPS-TC has been tested in real-time in both coupled and uncoupled modes over the past several tropical cyclone seasons in the Pacific and Atlantic basins at a horizontal grid spacing of 5 km. An evaluation of a large sample of real-time forecasts for the 2010 and 2011 seasons in the Atlantic basin reveals that the COAMPS-TC predictions have smaller intensity errors than other real-time dynamical models for forecasts beyond the 30 h time. Real-time forecasts for Hurricane Irene (2011) illustrate the capability of the model to capture both the intensity and the fine-scale features (e.g., eyewall, rainbands), in agreement with observations. The results of this research highlight the promise of high-resolution deterministic and ensemble-based approaches for tropical cyclone prediction using COAMPS-TC.

1. Introduction

A dramatic scenario played out during August 2011 as Hurricane Irene threatened many communities along the U.S. Eastern Seaboard, from Florida to New England. Basic questions such as where Irene would track and how strong it would become had profound implications for the millions of people in its path and billions of dollars in property that were vulnerable. The potential impact of tropical cyclones on military operations can also be enormous. An extreme example is the infamous Typhoon Cobra, also known as Halsey's Typhoon after Admiral William Halsey, which struck

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the U.S. Navy's Pacific Fleet in December 1944 during World War II. Three destroyers were lost, and a total of 790 sailors perished. More recently during Irene, the decision to sortie Navy assets from Norfolk, VA and other ports along the Eastern Seaboard many days in advance of the storm was critically dependent on forecasts of Irene's track, intensity (maximum sustained wind speed at the surface), and storm structure (such as the size of the storm or radius of key wind speed thresholds). In the N.W. Pacific, recently the Navy Pacific Fleet in the Philippine Sea was impacted by Typhoon Nanmadol, which exhibited erratic movement and was poorly forecasted.

The demand for more accurate tropical cyclone forecasts with longer lead times is greater than ever due to the enormous economic and societal impact. There has been steady and methodical improvement of tropical cyclone (TC) track prediction; a three-day tropical cyclone track forecast today is as skillful as a one-day forecast was just 30 years ago. However, there has been almost no progress in improving TC intensity and structure forecasts due to a variety of reasons ranging from a lack of critical observations under high wind conditions and in the TC environment to inaccurate representations of TC physical processes in numerical weather prediction (NWP) models. Advances in high-resolution TC modeling and data assimilation are thought to be necessary to significantly improve the performance of intensity and structure prediction. To this end, the Naval Research Laboratory (NRL) in Monterey, CA, has developed the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC), a new version of COAMPS designed specifically for high-resolution tropical cyclone prediction.

2. COAMPS-TC Description

The COAMPS-TC system comprises data quality control, analysis, initialization, and forecast model sub-components. The Navy Variational Data Assimilation System (NAVDAS[1]) is used to blend observations of winds, temperature, moisture, and pressure from a plethora of sources such as radiosondes, pilot balloons, satellites, surface measurements, ships, buoys, and aircraft with a model first guess field to produce the analysis. Enhancements to the NAVDAS system[2] for COAMPS-TC include the addition of synthetic observations that define the TC structure and intensity based on the TC reports in real-time from the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC). Also, as part of the TC analysis procedure, the pre-existing circulation in the COAMPS-TC first guess fields is relocated to allow for an accurate representation of the TC position during the analysis. Following this step, the analyzed fields are initialized to reduce the generation of spurious, high-frequency atmospheric gravity waves. The sea surface temperature is analyzed directly on the model computational grid using the Navy Coupled Ocean Data Assimilation (NCODA[3]) system, which makes use of all available satellite, ship, float, and buoy observations. Both the NCODA and NAVDAS systems are applied using a data assimilation cycle in which the first guess for the analysis is derived from the previous short-term forecast.

The COAMPS-TC atmospheric model uses the non-hydrostatic and compressible form of the dynamics and has prognostic variables for the three components of the wind (two horizontal wind components and the vertical wind), the perturbation pressure, potential temperature, water vapor, cloud droplets, raindrops, ice crystals, snowflakes, graupel, and turbulent kinetic energy.[4] Physical parameterizations include representations of cloud microphysical processes,[5] convection,[6] radiation,[7] boundary layer processes,[4] and surface layer fluxes.[8,9] The COAMPS-TC model contains a representation of dissipative heating near the ocean surface, which has been found to be important for tropical cyclone intensity forecasts.[10] The model also contains an optional advective scheme for scalars that preserves monotonicity and positive definiteness. The COAMPS-TC system uses a flexible nesting design that has proven useful when more than one storm is present in a basin at a given time as well as special options for moving nested grid families that independently follow individual tropical cyclones.

The COAMPS-TC system has the capability to operate in a fully coupled air–sea interaction mode.[11] The atmospheric module within COAMPS-TC is coupled to the NRL-developed Navy Coastal Ocean Model (NCOM[12]) to represent air–sea interaction processes. The COAMPS-TC system has an option to predict ocean surface waves, and the interactions between the atmosphere, ocean circulation, and waves using the Simulating WAves Nearshore (SWAN) model. A sea spray parameterization can be used to represent the injection of droplets into the atmospheric boundary layer due to ocean surface wave breaking and shearing.

3. Real-time Tropical Cyclone Forecasts

COAMPS-TC has been tested in real-time in both coupled and uncoupled modes over the past several tropical cyclone seasons in the Pacific and

Atlantic basins. These real-time tests have been conducted in conjunction with the National Oceanic and Atmospheric Administration (NOAA) sponsored Hurricane Forecast Improvement Project (HFIP), which is focused on accelerating the improvement in hurricane intensity forecasts. In these real-time applications, the atmospheric portion of the COAMPS-TC system makes use of horizontally nested grids with grid spacing of 45, 15, and 5 km. The 15- and 5-km grid-spacing meshes track the TC center, which enables the TC convection to be more realistically represented on the finest mesh in an efficient manner. The forecasts make use of the Navy or the NOAA global model for lateral boundary conditions.

The model is typically run four times daily for the W. Atlantic, E. Pacific, and W. Pacific regions and is triggered by the NHC and JTWC warning message (which contains observational estimates of the storm position and intensity) when a storm reaches a 30 knot intensity. The forecasts are routinely disseminated in real-time to NHC, JTWC, and HFIP researchers. The forecast graphics are also available in real-time at http://www.nrlmry.navy.mil/coamps-web/web/tc.

3.1. *COAMPS-TC atmospheric model forecasts*

Real-time COAMPS-TC forecasts have been conducted using U.S. Department of Defense High Performance Computing (HPC) platforms over the past several years. An example of the intensity forecast performance of COAMPS-TC for a large number of cases (more than 450 cases at the 24 h forecast time) in the W. Atlantic region for the 2010 and 2011 seasons is shown in Fig. 1 (for a homogeneous statistical sample). The COAMPS-TC model had the lowest intensity error of any dynamical model for the 36–120-h forecast times, which is an important period for forecasters and decision makers. Other numerical models included in this analysis are operational models run by NOAA (HWRF, GFDL), and the Navy's current operational limited area model (GFDN). This promising performance is a result of a large effort devoted to developing and improving COAMPS-TC over the past several years. Key aspects of the COAMPS-TC system that have contributed most to the forecast intensity skill improvement (as deduced from sensitivity tests) include: (i) new synthetic observations and data assimilation system modifications; (ii) modified turbulence parametrization (in particular the mixing length) in and above the boundary layer; (iii) surface drag, heat, and moisture exchange[10] consistent with recent field campaigns; and (iv) fidelity of the microphysical parametrization.

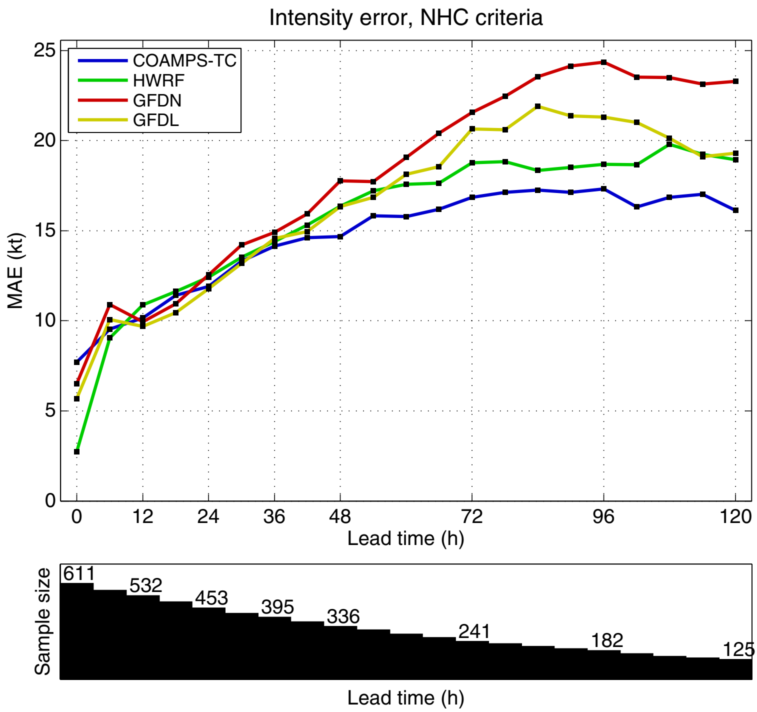


Fig. 1. Wind speed mean absolute error (MAE) (knots; 1 knot = 0.514 m s^{-1}) as a function of forecast time for the 2010 and 2011 seasons in the Atlantic basin for a homogeneous statistical sample. The numerical models included in this analysis are the Navy's COAMPS-TC, operational models run by NOAA (HWRF, GFDL), and the Navy's current operational limited area model (GFDN). The number of cases is shown at the bottom. The intensity errors are computed relative to the best track.

An example of a real-time COAMPS-TC forecast for the recent Hurricane Irene is shown in Fig. 2. The composite National Weather Service radar reflectivity is shown on the left panel near the time of landfall in North Carolina at 1148 UTC 27 August 2011 and the COAMPS-TC predicted radar reflectivity at 36 h valid at 1200 UTC is shown on the right panel. The COAMPS-TC forecast shown in Fig. 2 is for the model second grid mesh (15 km horizontal resolution). The model prediction was accurate in the track (skill similar to other dynamical models), eventual landfall location (Fig. 2), storm intensity (Fig. 4), as well as the structure and size (from a qualitative perspective), an especially important characteristic of this particular storm in such close proximity to the U.S. East Coast. One noteworthy aspect of Irene was its large size, with tropical storm

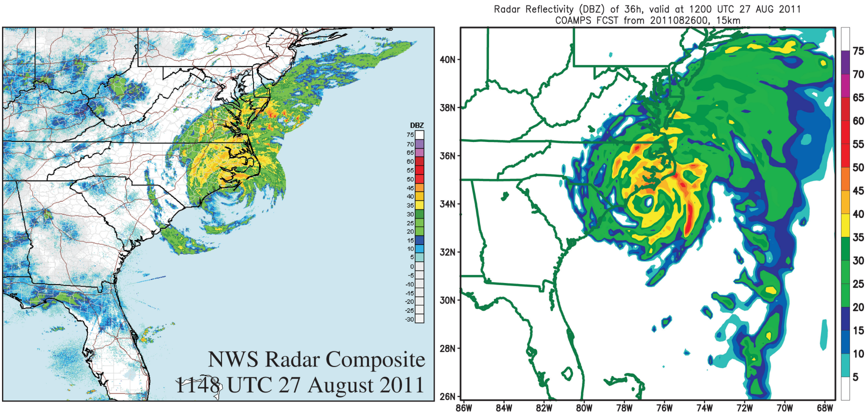


Fig. 2. The NWS composite radar reflectivity (from NOAA) valid at 1148 UTC 27 August 2011 (left) (source NOAA) and the COAMPS-TC 36-h forecast radar reflectivity performed in real time and valid at 1200 UTC 27 August (right) for Hurricane Irene. The COAMPS-TC reflectivity is shown for the second grid mesh, which has a horizontal resolution of 15 km.

force winds (17.5 $\mathrm{M\,s^{-1}}$ or 34 knots) extending radially outward from the eye for nearly 300 km. The large size of Irene is also apparent in the observed radar reflectivity in Fig. 2. The COAMPS-TC prediction captures the large areal extent of the precipitation field, as well as its asymmetry about the TC center (most of the precipitation is north and east of the center). This large shield of heavy precipitation caused severe river flooding as it slowly moved north through the mid-Atlantic and Northeast U.S. The simulated radar reflectivity for the COAMPS-TC grid mesh 3 (5 km horizontal resolution), shown in Fig. 3, illustrates the capability of the model to capture the finer-scale features, such as the eyewall and rainbands, in generally good agreement with the observed reflectivity. Sensitivity tests (not shown) indicate that the synthetic observations and TC-related data assimilation system modifications, along with the in-cloud turbulent mixing representation, are important for proper simulation of Irene's structure. It should also be noted that COAMPS-TC makes use of a 1.5 order closure turbulence parametrization that predicts turbulent kinetic energy (TKE) and includes advection of TKE. We hypothesize that the advection of TKE may be important for the proper representation of the turbulence evolution within the hurricane boundary layer beneath and near the eyewall.

Overall, the Navy's COAMPS-TC real-time intensity predictions of Hurricane Irene were more skillful than the other leading operational

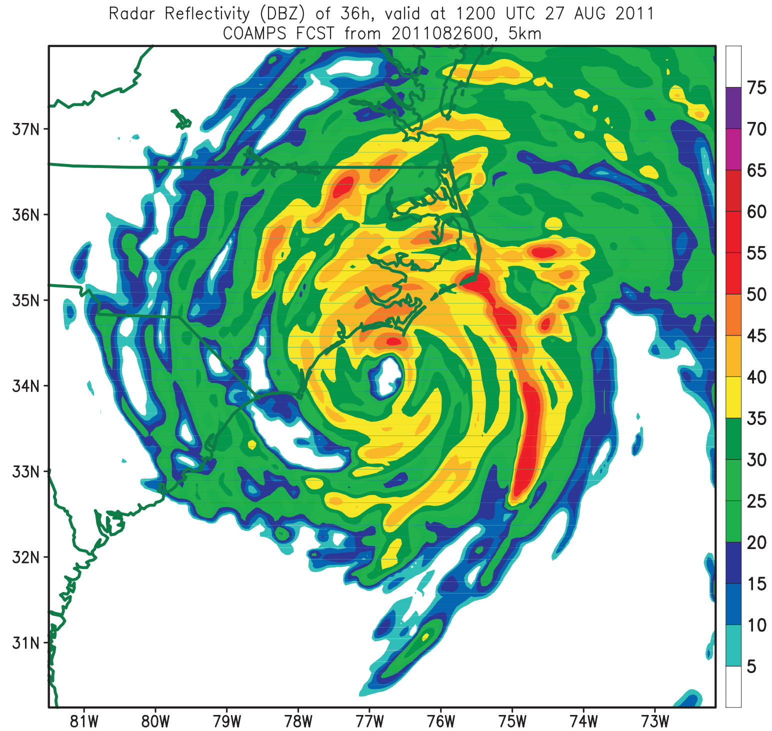


Fig. 3. The COAMPS-TC 36-h forecast radar reflectivity valid at 1200 UTC 27 August for the third grid mesh, which has a horizontal resolution of 5 km.

governmental forecast models, as shown in Fig. 4. All of the available models except for COAMPS-TC had a tendency to over-intensify Irene, often by a full Saffir-Simpson category or more. These real-time COAMPS-TC forecasts were used by forecasters at the National Hurricane Center as part of an experimental HFIP multi-model ensemble. The COAMPS-TC consistently provided accurate real-time intensity forecasts during the period 23–28 August 2011, when critical decisions were made by forecasters and emergency managers including evacuations.

3.2. *COAMPS-TC ensemble forecasts*

While research is ongoing to improve deterministic atmospheric forecasts through advancements to the forecast model and more accurate estimates of the initial state, simultaneously there has been interest in obtaining probabilistic information derived from ensemble forecasts. An ensemble

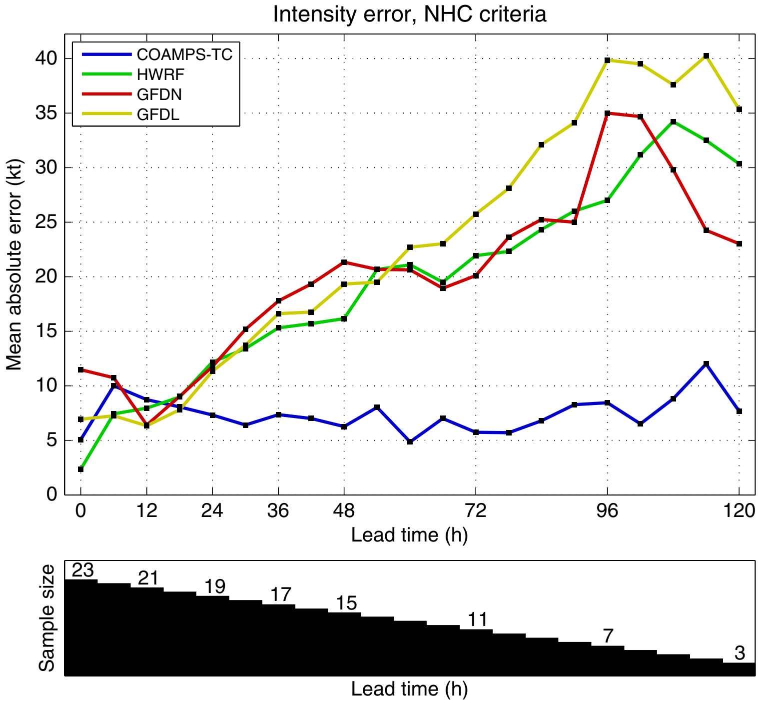


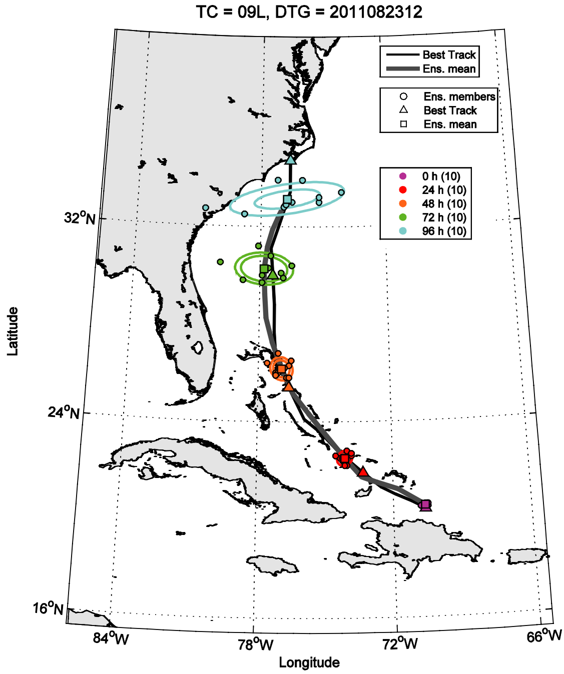
Fig. 4. Wind speed MAE (knots) as a function of forecast time for Hurricane Irene for a homogeneous statistical sample. The numerical models included in this analysis are the Navy's COAMPS-TC, operational models run by NOAA (HWRF, GFDL), and the Navy's current operational limited area model (GFDN). The number of cases is shown at the bottom. Only forecasts after Irene has moved away from Hispaniola are shown here. The intensity errors are computed relative to the best track.

of forecasts from equally plausible initial states and model formulations offer a computationally feasible way of addressing inevitable forecast uncertainties, offering improved forecasts through ensemble statistics such as mean quantities, as well as quantitative estimates of forecast error and variance. Although the concept of ensemble modeling is relatively simple, the performance of an ensemble forecast system is very sensitive to the basic ensemble architecture. At the Naval Research Laboratory, we are designing new ensemble methods for both the global and mesoscale atmospheric forecast systems. Because of the high computational demands associated with ensemble development and verification (especially when one is interested in severe or rare events), exceptional computational resources are necessary to perform this research.

A new COAMPS-TC ensemble system that is capable of providing probabilistic forecasts of TC track, intensity, and structure has been developed by scientists at NRL in Monterey, CA. This system makes use of the community-based Data Assimilation Research Testbed (DART[13]) developed at the National Center for Atmospheric Research, which includes various options for Ensemble Kalman Filter (EnKF) data assimilation. The COAMPS-TC DART system constitutes a next generation data assimilation system for tropical cyclones that uses flow dependent statistics from the ensemble to assimilate observational information on the mesoscale.

A real-time COAMPS-TC ensemble system was run in a demonstration mode in 2011 for the W. Atlantic, E. Pacific, and W. Pacific regions. The system was comprised of an 80-member COAMPS-TC cycling data assimilation ensemble on three nested grids with horizontal spacing of 45, 15, and 5 km. For each TC initiated by either NHC or JTWC, the COAMPS-TC ensemble was initialized by interpolating global forecast fields from the 80-member GFS-EnKF system[14] to the three nested grids, which were centered on the storm. Six-hour forecasts were made four times daily to provide background estimates for the assimilation of observations from surface stations, ship data, radiosonde ascents, cloud-track wind retrievals, and aircraft data using the DART EnKF. In addition to these conventional datasets, the NHC and JTWC TC position estimates were directly assimilated with the EnKF system. Under-sampling issues in the data assimilation procedure associated with the finite ensemble size were controlled by limiting the spatial influence of observations with a static localization radius of 1,000 km, as well as applying a spatially and temporally varying inflation factor[15] to the prior ensemble perturbations. For effective usage of the high-resolution capability of COAMPS-TC, a two-way interactive data assimilation procedure was implemented. In this algorithm, the innovations were defined using the highest resolution nest that contained the observation. These innovations were used to update the COAMPS-TC fields on all three grids. Furthermore, observations contained outside of a nest were allowed to update the fields within the nest.

Ten-member forecasts were performed twice daily to five days using the same three nested grid configuration as the data assimilation ensemble. The first 10 members of the data assimilation ensemble were used to define the forecast ensemble. Lateral boundary conditions for the forecast ensemble were drawn from the GFS-EnKF ensemble forecast. Examples of probabilistic products for Hurricane Irene are shown in Fig. 5 for both track (top panel) and intensity (bottom panel). This is a real-time



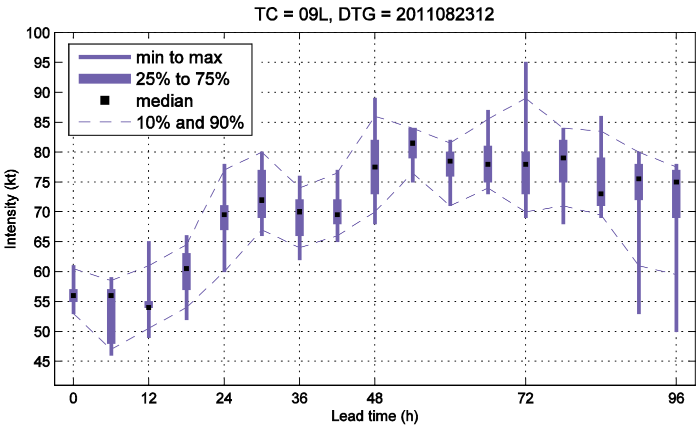


Fig. 5. Probabilistic products from the COAMPS-TC ensemble for Hurricane Irene corresponding to the track (top panel) and intensity (bottom panel). This real-time forecast was initialized at 1200 UTC 23 August, which is approximately four days prior to landfall. The probabilistic track product shows the TC position from the individual ensemble members every 24 h and ellipses that encompass 1/3 and 2/3 of the ensemble members. The intensity (knots) distribution is shown as a function of forecast lead time (hours) with the minimum value, maximum value and various quantiles of the ensemble distribution shown as denoted by the legend.

forecast initialized at 1200 UTC 23 August, which is four days prior to landfall. The probabilistic track product shows the TC position from the individual ensemble members every 24 h and ellipses that encompass 1/3 and 2/3 of the ensemble member forecast positions. Note that the observed landfall location of the eye (see Fig. 2) was within the ensemble distribution, although the ensemble mean landfall was approximately 12 h later than observed. The probabilistic intensity product (lower panel) shows a considerable spread among the members, particularly beyond 84 h, just prior to landfall. These products can be extremely valuable to assess the uncertainty in both track and intensity forecasts, and NRL is currently developing these capabilities and products further.

3.3. *Coupled COAMPS-TC forecasts*

The COAMPS-TC system was run in a fully coupled mode, interactive with NCOM, during the Office of Naval Research sponsored Interaction of Typhoon and Ocean Project (ITOP) during the summer and fall of 2010. An example of a fully coupled COAMPS-TC forecast for Typhoon Fanapi performed in real-time is shown in Fig. 6. The NCOM ocean model was applied using a 10-km horizontal grid increment in this example, and the finest mesh for the atmospheric model used a 5-km grid increment. The atmosphere and ocean fluxes were exchanged every ocean model time step. The COAMPS-TC predicted track (red) from a 90-h real time forecast valid at 0600 UTC 19 September 2010 is quite close to the observed or best track (black). The sea surface temperature, shown in color shading, indicates significant cooling was predicted by COAMPS-TC during the passage of Fanapi due to enhanced mixing by the strong near-surface winds of the typhoon. The predicted cooling of the sea surface temperatures of 2–4°C is in agreement with estimates from *in situ* and remote sensing observations in this region. The negative impact of the ocean cooling underneath the tropical cyclone can reduce the TC intensity and broaden the tropical cyclone secondary circulation, which underscores the importance of properly representing these air–sea interaction process.[4,11]

A joint Navy/Air Force Hurricane Hunter program was in its demonstration phase in 2011 with Airborne Expendable Bathythermographs (AXBTs) being deployed from WC-130J hurricane reconnaissance aircraft in order to improve the initialization and validation of coupled models such as COAMPS-TC. Over 30 AXBTs were deployed from Air Force Hurricane Hunter aircraft in Irene as it approached landfall on Cape Hatteras.

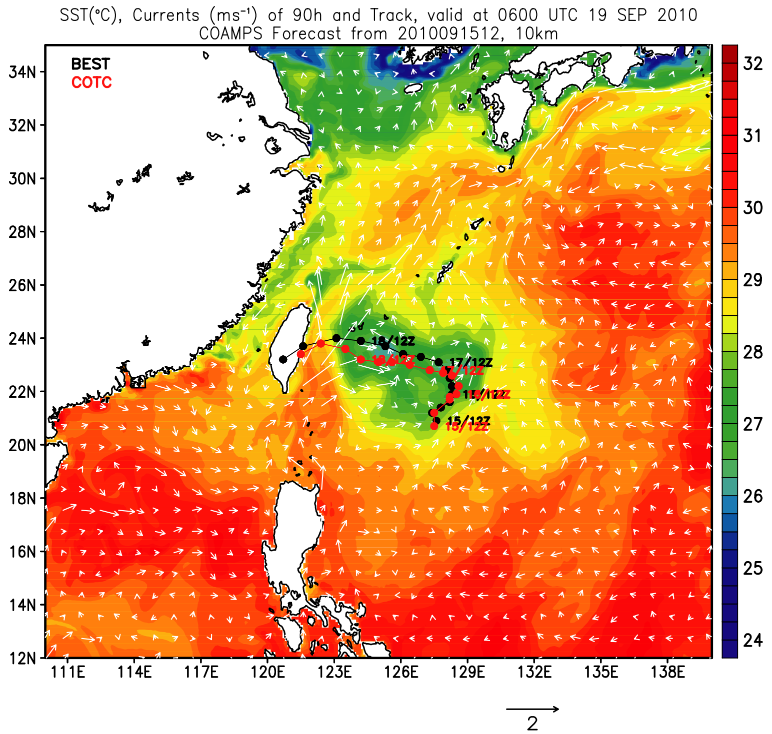


Fig. 6. The COAMPS-TC predicted track (red) for Typhoon Fanapi from a 90-h real-time forecast valid at 0600 UTC 19 September 2010 and the observed best track (black). The sea surface temperature (°C) is shown in color shading and indicates significant cooling during the passage of Fanapi. The surface currents are shown by the white vectors.

Assimilation studies are currently being carried to assess the impact of these AXBTs on the coupled model skill. These new observations supplement previous studies[4,11] of hurricane-induced cooling and may further help document the existence of ocean mixing or advective processes (and cooling of the sea surface) along the storm track and in coastal regions that may have slowed the intensification of Irene.

4. Summary

The prediction of the tropical cyclone track, and even more so, the tropical cyclone intensity, remain among the greatest challenges facing meteorology today. The results of this research highlight the promise of high-resolution deterministic and ensemble-based approaches for tropical cyclone prediction using models such as COAMPS-TC. During the past several tropical cyclone seasons in the Pacific and Atlantic basins, COAMPS-TC has been tested in real-time in both coupled and uncoupled modes at a horizontal resolution of 5 km. An evaluation of a large sample of real-time forecasts for the 2010 and 2011 seasons in the Atlantic basin reveals that the COAMPS-TC predictions have smaller intensity errors than any other real-time dynamical model beyond the 30 h forecast time. Recent real-time forecasts of Hurricane Irene (2011) illustrate the capability of COAMPS-TC to capture both the intensity and the fine-scale features (e.g., eyewall, rainbands), in agreement with observations. Real-time forecasts of Typhoon Fanapi in the W. Pacific performed in support of the ITOP experiment in 2010 accurately predicted not only the track and intensification, but also captured the sea surface cooling induced by the mixing and upwelling in agreement with satellite measurements.

While real-time COAMPS-TC has accurately predicted the evolution of Irene, Fanapi, as well as other tropical cyclones (not shown), there are a number of examples that were not predicted as well. These storms, and the data collected during their life cycle, provide opportunities to study and obtain a greater appreciation of the complex physics and interactions that occur in these systems, and to use this information to further improve the COAMPS-TC modeling system.

This research will lead to new capabilities in the form of mesoscale TC ensemble forecasts, providing the Navy with probabilistic forecasts of tropical cyclone intensity and structure for the first time. It is also expected that this research will help motivate new field campaigns, which focus on the key measurements needed to further advance our understanding of the convective structure and dynamics of these systems, as well as provide forecast validation. The flexibility of the COAMPS-TC design will also allow us to test more advanced physics and numerics in an effort to gain a better physical understanding of the model's intensity forecast skill.

Acknowledgments

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